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Translation of "Eksperimental'noye issledovaniye ispareniya kapel' v usloviyakh vysokikh temperatur i davleniya"

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EXPERIMENTAL INVESTIGATION OF DROPLET VAPORIZATION UNDER CONDITIONS OF HIGH TEMPERATURES AND PRESSURES*

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1. GENERAL OBSERVATIONS

In order to design combustion chambers for rocket engines it is necessary to have data on the rate of vaporization of the fuel droplets. According to the present day concepts pertaining to the energy process in engines, the vaporization of the droplets in the combustion chamber plays a very important, in some cases even decisive, role. Not only the process of mixture formation but also the stability of operation of certain types of engines is associated with the rate of vaporization of the droplets. Notwithstanding the considerable number of studies that have been devoted to this question (e.g., refs. 1 and 2), both the specific features of the process of intense vaporization of droplets and the characteristics associated with the vaporization of droplets under conditions of high pressures have been almost entirely neglected.

In this article a brief description is presented of an experimental investigation whose fundamental object was to obtain data on the vaporization of droplets in a gas stream under high temperature and pressure conditions. Since the vaporization of droplets plays an important part in a number of processes of the chemical and power production industries, the data obtained in this investigation may also have a wider application.

For the investigation of the heat and mass transfer processes between the droplets and the gas stream under conditions of high pressure, it was found necessary to design a relatively complex experimental apparatus, a general view of which is given in figure 1. On this apparatus, the vaporization of droplets of water, 96-percent ethyl alcohol, and the fuel TC-1 (kerosene) was investigated. The droplets were vaporized in an airstream. The tests were conducted at pressures from 10 to 60 atmospheres in a range of airstream temperatures from 90° to 500° C. Another relatively simple apparatus was used for conducting the investigation at high temperature. The vaporization of water from a surface of a porous sphere at atmospheric pressure was studied in this apparatus. In these tests the temperature of the gas stream about the sphere was

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maintained constant at approximately 2800° C.

2. EXPERIMENTAL APPARATUS FOR INVESTIGATING THE VAPORIZATION OF DROPLETS IN THE REGION OF HIGH PRESSURES

The gas stream in this apparatus was produced by the use of compressed air. The air entered the pneumatic system from standard tanks under a pressure of 150 atmospheres. The air was conducted along high pressure mains to a valve 1 (fig. 2) and then entered the silica gel adsorber 2, which absorbed the moisture from the air. To clean the silica gel dust and other mechanical admixtures from the air, filters 3 were placed behind the adsorber. After the air passed through the filters, it then entered the air reducer 4. The pressure behind the reducer was adjusted to correspond with the given operating conditions of the apparatus and could be any value between the limits 10 and 60 atmospheres. The air, reduced to the operating pressure, passed through the receiver 5 and the shutoff valve 6 into the coil 7 placed in the tube furnace and in this way was preliminarily heated. Valve 8 served for purging the air from the system. From the coil, the air entered the thick-walled pipe 9, which was placed in the other four furnaces 10. This pipe had an internal diameter of 26 millimeters and a wall thickness of 4 millimeters and was filled with pieces of porcelain no larger than 4 millimeters in size. As a result, the air in the pipe was well mixed and uniformly heated. The coil and pipe were made of X18H9T steel. Furnaces with thermal regulators were used to heat the air tube. The temperature in the furnaces was controlled by Chromel-Alumel thermocouples in the vapor with cylindrical millivoltmeters 11 (fig. 2).

The pipe supplying the heated air ended in a widened portion followed by a nozzle 1 (fig. 3). The greatest diameter of the nozzle was 40 millimeters; the exit section of the nozzle had a diameter of 16 millimeters. In front of the widened part of the nozzle in pipe 2 were attached two round plates with a large number of 0.5 millimeter-diameter openings. The nozzle and plates were made of rustless steel. The pieces of porcelain in the supply pipe rendered the flow turbulent and equalized the velocity and temperature fields over the pipe cross section. The perforated plates reduced the scale of the turbulence, while the widening part of the pipe and the nozzle itself lowered the intensity of the turbulent pulsations somewhat.

According to the theory of free flow of a jet (ref. 3), the airstream behind a nozzle has a core of constant velocities. The vaporizing droplets were situated at a distance of 6 millimeters from the nozzle and were found to be in the core of the stream. The direct measurement of the velocity in the exit section of the nozzle of the pneumatic pipe showed that the velocity at a distance of 2 millimeters from the wall of the nozzle differs from the axial velocity by no more than 8 percent. This permitted the assumption to be made that the field of velocities at the nozzle exit was uniform and the value of the velocity in the working section of the core of the stream was equal to the value of the velocity in the exit section of the nozzle.

The entire section after the air supply pipe (including the wide part and nozzle) was situated within the thick-walled chamber 12 (fig. 2), which was

designed for high pressure. This chamber consisted of a cylindrical steel body 3 (fig. 3) with forward and rear covers 4 and 5 and rings 6 with plane-parallel optical windows 7. The glass in the rings was made tight with the bushings 8. The covers of the body served as flanges for pipe 2 which supplied the hot air, and pipe 9, which conducted the hot air away. In the upper part of the chamber was placed a knob 13 (fig. 2) on which a device was mounted for supplying the working liquid to the chamber.

In cases when the temperature of the internal walls of the chamber exceeded 100° to 150° C, cooling air was supplied to the annular space 10 (fig. 3) through a reducer 14 (fig. 2) and a two-way valve 15 (fig. 2). After cooling the rings, the air passed into a collector 11 (fig. 3) and was admitted to the atmosphere through conduit 16 (fig. 2). The cavities of the chamber were made airtight with the aid of the packing 12 and 13 (fig. 3). The inner surface of the chamber was covered with insulation 14 (fig. 3).

The temperature of the airstream was measured by a thin Chromel-kopel‡ thermocouple placed in the brass body 1 (fig. 4). The thermal electromotive force was measured with a type PP potentiometer. The error in measuring the temperature of the stream did not exceed 3 percent. A capillary tube surrounded by a cooling sleeved passed inside the knob 2 (fig. 4). Water was used as a cooling liquid. The water entered from a tank 17 (fig. 2) and its consumption was regulated by a needle valve 18. The excess pressure in the tank was maintained with the aid of the reducer 19 and a check valve 20. A valve 21 served to relieve the tank pressure. The water was conducted away from the capillary cooling sleeve along a pipe 22. A Chromel-kopel‡ thermocouple with insulated thermoelectrodes 0.05 millimeter in diameter was placed in the capillary tube The end of the thermocouple together with the hot junction formed an accurate sphere from which the droplets were suspended at the time of the tests. The center of the sphere was located at a distance of 4 millimeters from the lower end of the tube.

The upper end of the tube was connected to the displacement device (fig. 4) that supplied the investigated liquid to the capillary tube. Upon issuing from the lower end of the tube, the liquid formed a droplet which, when it attained a certain size, fell on the sphere at the end of the thermocouple. The thermoelectromotive force was measured with a type PP potentiometer. The droplet was suspended on the thermocouple only when it was necessary to determine its temperature. For the measurement of the rate of vaporization, the droplets were suspended not on the thermocouple but on the ball formed at the end of the 0.05-millimeter-diameter Chromel wire. The center of the ball, as before, was at a distance of 4 millimeters from the lower end of the capillary tube. Special tests and computations indicated that, under the conditions of the experiment, the supply of heat through the wire was negligible.

The displacement device previously mentioned consisted of a frame attached to the knob of a rod 3 (fig. 4), a cylinder 4, and a supply screw 5. The needle valves 6, 7, and 8 were used to charge the cylinder with the working liquid, which was transferred from a tank 23 (fig. 2) through a filter 24 by compressed

‡Translation not available.

air. Between the cylinder and the frame was a ball joint 9 (fig. 4), which permitted easy removal of the upper part of the device. Liquid was supplied to the capillary tube by introducing the rod into the cylinder by means of the screw. The pressure in the chamber was measured by a class 0.5 spring manometer.

The airflow issuing from the nozzle 1 (fig. 3) and blowing past the droplet entered the receiver pipe 9 (fig. 3). Outside the chamber, this pipe had a sleeve 15 (fig. 3) that was cooled with water from the water pipe. The water entered the intersleeve space 16 (fig. 3) along pipe 25 (fig. 2) and was conducted away along pipe 26. The preliminarily cooled air in the receiver pipe entered the coil 27 immersed in the water flow conduit. The length of the coil was fully sufficient for cooling the air to the temperature of the water in the water supply pipe. From the coils, the air passed through a filter 28 and arrived at a measuring needle valve 29 which regulated the air consumption. The pressure drop in the needle was supercritical for all operating conditions of the apparatus. The air consumption varied between the limits 0.36 to 2.30 grams per second. After passing out of valve 30, the air entered the straight portion of the conduit, where its temperature, pressure, and quantity were measured. The air quantity was measured with a throttle disk 31 and a DT-50 differential manometer. The temperature of the flow was controlled with a thermocouple mounted in the special frame 32. From the straight part of the conduit, the air entered the cutoff valve 33 from which, depending on the position of the valve, it moved to the atmosphere or the gas holder 34. When a calibration was made of the throttle disk the air was led to a gas holder. The use of the gas holder was necessitated by the small values of the Reynolds numbers that occurred in the tests. These Reynolds numbers were below the limiting values, and thus the coefficient of consumption of the throttle disk varied as a function of the consumption. The error in measuring the consumption did not exceed 4 percent.

The rate of vaporization of the droplet was determined by the method of moving pictures. As it was vaporizing within the chamber, the droplet was projected on a moving picture film by means of a special optical system consisting of the light source 35 (fig. 2), condenser 36, light filter 37, objective 38, and microscope 39. By means of the special attachment 40, the microscope was connected with a type KC-50 moving picture camera 41. The droplet image obtained on the film was magnified from the actual 2 millimeter diameter of the droplet to the diameter of 14 to 15 millimeters; that is, the frame was entirely utilized. A white screen 42 was placed between the objective and the microscope. The droplet image was projected on this screen before photographing. At the instant the droplet fell from the end of the capillary tube onto the ball formed at the end of the filament, the screen was removed and the moving picture camera connected. A type MP02/D shunt motor 43 was used for driving the camera. A gear reducer with variable pinions 44 permitted the velocity of the film motion to be varied. In order to determine the scale of the image, the lower end of the capillary tube, whose true dimension was accurately known, was photographed on the film.

When the film was treated, the drop image was further magnified 20 times, and the diameter was measured with an accuracy up to 1 millimeter in two mutually perpendicular directions. This measurement technique was a necessary

consequence of the fact that the droplet did not always have a spherical shape. In further treatment of the experimental data, the diameter of the droplet was taken equal to the arithmetic mean of the measured values. At some interval of time, the diameter of the droplet was nearly equal to the diameter of the wire suspension ball. The moving picture frames corresponding to this time interval were not taken into account in working up the data, since the droplet vaporization under these conditions could have been distorted.

3. DESCRIPTION OF EXPERIMENTAL APPARATUS FOR THE INVESTIGATION OF THE VAPORIZATION FROM THE SURFACE OF A POROUS SPHERE IN THE REGION OF HIGH TEMPERATURES

For the investigations in the high-temperature region another experimental apparatus was used, in which the investigated liquid was evaporated from the surface of a porous sphere. Water was chosen as the liquid to be studied. A porous sphere with a diameter of 5.3 millimeters provided a model of an evaporating droplet. The sphere was sintered from fine metallic granules prepared on a bronze base. The water was supplied to the center of the sphere with a sprayer and needle for subcutaneous injection. The sphere was attached on the needle by means of a screw thread.

In this apparatus a high-temperature gas stream was produced by an oxyacetylene burner placed in a vertical position. The velocity of the stream was measured by a cooled pneumatic tube of stainless steel. On the tube was wound a thin layer of ordinary cotton which started at a distance of 0.8 to 1 millimeter from the receiving end of the tube. When the pneumometric tube was situated in the stream, the cotton was impregnated with water from time to time. In this way, the surface of the tube always remained wet. The cooling by evaporation was found to be sufficiently effective, and the receiving end of the tube did not fuse.

The sphere was placed in the hot gas produced by the burner at a distance of 7 millimeters from the tip and was maintained in that position for a given time. The rate of vaporization of the liquid which extruded onto the surface of the porous sphere was measured by weighing the entire apparatus on analytical scales. The weighing was done before and after each test. The time of vaporization was determined by a timing device and was selected between the limits 60 and 68 seconds. During this time, about 1 gram of water evaporated from the surface of the sphere.

The part of the needle situated in the stream was cooled by the same method as was used for the pneumometric tube. The thin layer of cooling cotton started from a distance of 1 to 1.2 millimeters from the surface of the sphere and covered the entire needle. The layer ended with a thickening located outside the flow. The cotton wetted by water during the test did not manage to dry completely and, in contrast to the cooling of the pneumatic tube, additional impregnation of the cotton was not necessary. It should be remarked that, because of the cooling produced by the vaporization, the temperature of the wall of the needle was near the temperature of the surface of the liquid film

vaporizing from the porous sphere. Hence, the water supplied to the center of the sphere assumed a temperature approximately equal to the temperature of equilibrium vaporization. In accordance with the experimental and theoretical data presented in reference 4, the temperature of a jet in the section where the porous sphere was situated was taken to be 2800° C.

A special series of tests devoted to the measurement of the temperature of the liquid film vaporizing from the surface of the sphere was conducted on the described apparatus. The temperature was measured by a Nichrome-constantan thermocouple with 0.1-millimeter-diameter thermoelectrodes made of enameled wire. The thermocouple was placed in an annular channel on the surface of the sphere, and its ends were led along the previously mentioned needles under the layer of the cooling cotton. The thermocouple was calibrated in the final assembled form.

4. PROCEDURE OF CONDUCTING THE TESTS

As was mentioned previously, the vaporization of droplets of distilled water, 96 percent ethyl alcohol, and the fuel TC-1 (kerosene) was studied on the apparatus for investigating the processes of vaporization of droplets in the region of high pressures. The droplets were vaporized in an airstream for various velocities, temperatures, and pressures of the surrounding medium in correspondence with the proposed problem. Since it was proposed to work up the experimental data with the criteria of similitude, all the quantities required for computing these criteria were measured in the tests.

Before investigating the dependence of the processes of vaporization and heat exchange of the droplets on the temperature and pressure, it was necessary to study the dependence of these processes on the hydrodynamic conditions at constant temperature and pressure. For this purpose the rates of vaporization of the water droplets for various Reynolds numbers were measured in the first series of tests. The Reynolds numbers were varied between 115 and 455 by changing the consumption of the air blown around the droplet. The pressure in the chamber was maintained at 11 atmospheres and the temperature of the airstream was held at 322° C.

The droplets of water were vaporized on the accurate sphere formed at the end of the Chromel wire. The droplet diameter varied from 2 to 1 millimeter. The Reynolds number was computed from the arithmetic mean diameter of the droplet over the period of evaporation. For each regime the tests were repeated five to ten times. In the majority of cases the difference between the rates of vaporization of the droplet under similar conditions did not exceed 6 percent. Control measurements were conducted at the end of each series of tests. For this purpose the apparatus was adjusted for one of the regimes and the measurements were made repeatedly.

A second series of tests on water droplets was conducted for various temperatures from 103° to 489° C and a constant discharge of air was blown past the droplet. The pressure was maintained at 11 atmospheres. The Reynolds number was changed only by the variation of the viscosity of the air with temperature. The viscosity of the air was related to the temperature of the flow. It

should be remarked that since the effect of the Reynolds number on the process of heat exchange and vaporization of a droplet was examined in the first series of tests, it was not necessary that the Reynolds number remain constant in the succeeding tests.

A third series of tests with water droplets was conducted at various pressures from 11 to 61 atmospheres. The temperature of the flow was varied from 221° to 352° C, and the air discharge about the droplet was maintained constant.

A special series of tests was devoted to measuring the temperature of the droplet. This measurement was conducted for all regimes.

The limits of variation of the parameters in the tests with the droplets of water are shown in table 1.

The droplets of 96 percent ethyl alcohol were vaporized in an airstream at various pressures and temperatures. The sphere formed at the end of the filament had a diameter of about 1.0 to 1.2 millimeters, while the diameter of the droplet varied during evaporation from 1.8 to 1.2 millimeters. In the tests with ethyl alcohol the air discharge about the droplet was maintained constant, while the Reynolds number computed from the mean diameter of the droplet during the period of vaporization varied only because of the variation of the viscosity of the air with the temperature.

The first series of tests with the alcohol was conducted at various temperatures. The pressure was maintained at 11 atmospheres. The second series of tests was conducted for variable pressure while the temperature of the airflow varied between small limits. The temperature of the droplets of the ethyl alcohol was measured for all regimes.

Table 2 gives the limits of variation of the parameters of the airflow in the tests with droplets of 96 percent ethyl alcohol.

The first series of tests with droplets of TC-1 fuel (kerosene) was conducted for various temperatures with the pressure at 11 atmospheres. As in the tests with water and ethyl alcohol, the Reynolds number was varied only because of the variation of the viscosity of air with temperature. The air discharge was maintained constant. The second series of tests was conducted for variable pressure. The temperature hardly varied. In order to determine the limits of variation of the temperature of the droplet of TC-1 fuel during vaporization, the droplet temperature was measured at the start and at the end of the vaporization. The droplets of TC-1 fuel changed their diameter from 1.8 to 1.2 millimeters during the test. The diameter of the wire bead on which the droplet was suspended was chosen to be 1.0 to 1.2 millimeters.

In table 3 the measured parameters of the airflow in the tests with the droplets of TC-1 fuel are given.

5. RESULTS OF THE EXPERIMENTAL INVESTIGATION

The chief experimental data obtained on the apparatus described above are presented in tables 4 to 8. The following notations are used in the tables: d, diameter of droplet; τ, time; G_v, mass flow of air over the droplet; G, weight of vaporizing liquid; u, velocity of airflow; t_c, temperature of airflow; P, pressure; t_k, temperature of equilibrium vaporization of the droplet; Re, Reynolds number computed for the mean droplet diameter during the period of vaporization and for air conditions at the determined temperature of the air flowing past the droplet. The derivative of the square of the droplet diameter with respect to time $d(d^2)/d\tau$ maintained a constant value over the investigated range of variation of the droplet diameter. The mean experimental values of the quantities $d(d^2)/d\tau$ and $dG/d\tau$, obtained by repeated measurements, are given in the tables.

In conclusion we may note that the method of computing the Reynolds number from the arithmetic mean diameter of the droplets under the test conditions does not lead to any considerable error and can be based on the following considerations. The maximum possible change of the droplet diameter in our tests from $d_o = 2$ millimeters to $d_o/2$ was observed during the vaporization of water droplets. It can readily be shown that the actual mean diameter of the droplet is

$$\frac{\int_0^{\tau_k} (d_o^2 - k\tau)^{1/2} \cdot d\tau}{\tau_k} = \frac{7}{9} d_o$$

where $\tau_k = \frac{3\ d_o}{4k}$ is the time of vaporization of the droplet from d_o to $d_o/2$ and $k = d(d^2)/d\tau = \text{const}$. The arithmetic mean diameter for this case was equal to $(d_o + d_o/2)/2$, that is, $3/4\ d_o$. Since in the least favorable case the actual mean diameter of the vaporizing droplet differed from the arithmetic mean by not more than 3.6 percent*, the Reynolds number may be computed from $d_{arith.mean}$ without introducing a large error. For the other investigated liquids this difference was even smaller and constituted a magnitude not exceeding 2 percent.

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*This result does not depend on the magnitude of $d(d^2)/d\tau$.

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National Aeronautics and
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TABLE 1

Test series	G_v, g/sec	Re	t_c, °C	P, atm
1	0.47-1.86	115-455	322	11
2	1.14	388-237	103-489	11
3	1.14	318-269	221-352	11-61

TABLE 2

Test series	G_v, g/sec	Re	t_c, °C	P, atm
1	1.14	394-301	91-259	11
2	1.14	331-328	196-200	11-41

TABLE 3

Test series	G_v, g/sec	Re	t_c, °C	P, atm
1	0.81	256-211	144-272	11
2	1.13	223-310	231-234	11-41

VAPORIZATION OF DROPLETS OF WATER

TABLE 4

$t_c = 322^\circ$ C; P = 11 atm

$t_k = 109^\circ$ C

Number	G_v, g/sec	Re	$\frac{d(d^2)}{d\tau} \cdot 10^6$, m^2/hr
1	0.47	115	527
2	.58	141	568
3	.68	167	607
4	.79	193	657
5	.90	220	696
6	1.00	246	724
7	1.11	272	778
8	1.22	298	831
9	1.33	324	851
10	1.43	350	869
11	1.54	377	892
12	1.65	403	950
13	1.75	429	963
14	1.86	455	979

TABLE 5

G_v = 1.14 g/sec

Number	P, atm	t_c, °C	t_k, °C	Re	$\frac{d(d^2)}{d\tau} \cdot 10^6$, m^2/hr
1	11	221	93	318	395
2	16	223	102	317	386
3	21	227	109	315	376
4	26	231	116	313	386
5	31	248	123	305	425
6	36	267	129	298	486
7	41	273	137	296	479
8	46	319	145	280	653
9	51	353	154	269	805
10	56	348	157	271	783
11	61	352	159	270	816

TABLE 6

VAPORIZATION OF DROPLETS OF 96 PERCENT ETHYL ALCOHOL

G_v = 1.14 g/sec

Number	P, atm	t_c, °C	t_k, °C	Re	$\frac{d(d^2)}{d\tau} \cdot 10^6$, m^2/hr
1	11	91	57	394	280
2	11	156	75	354	669
3	11	196	82	331	917
4	11	259	90	301	1465
5	16	197	88	330	851
6	21	197	94	330	823
7	26	198	100	330	803
8	31	199	104	329	788
9	36	200	107	329	772
10	41	200	110	329	739

TABLE 7

VAPORIZATION OF DROPLETS OF TC-1

FUEL (KEROSENE)

Number	P, atm	t_c, °C	G_v, g/sec	Re	$\frac{d(d^2)}{d\tau} \cdot 10^6$, m^2/hr
1	11	144	0.81	257	294
2	11	185	.81	241	691
3	11	232	.81	223	1360
4	11	272	.81	211	2100
5	31	234	1.13	309	903
6	41	231	1.13	310	716

TABLE 8

VAPORIZATION OF WATER FROM THE

SURFACE OF A POROUS SPHERE

u, cm/sec	P, atm	t_c, °C	t_k, °C	Re	$\frac{dG}{d\tau}$, g/sec
35.9	1	2800	90	190	0.016

Figure 1. - General view of experimental apparatus.

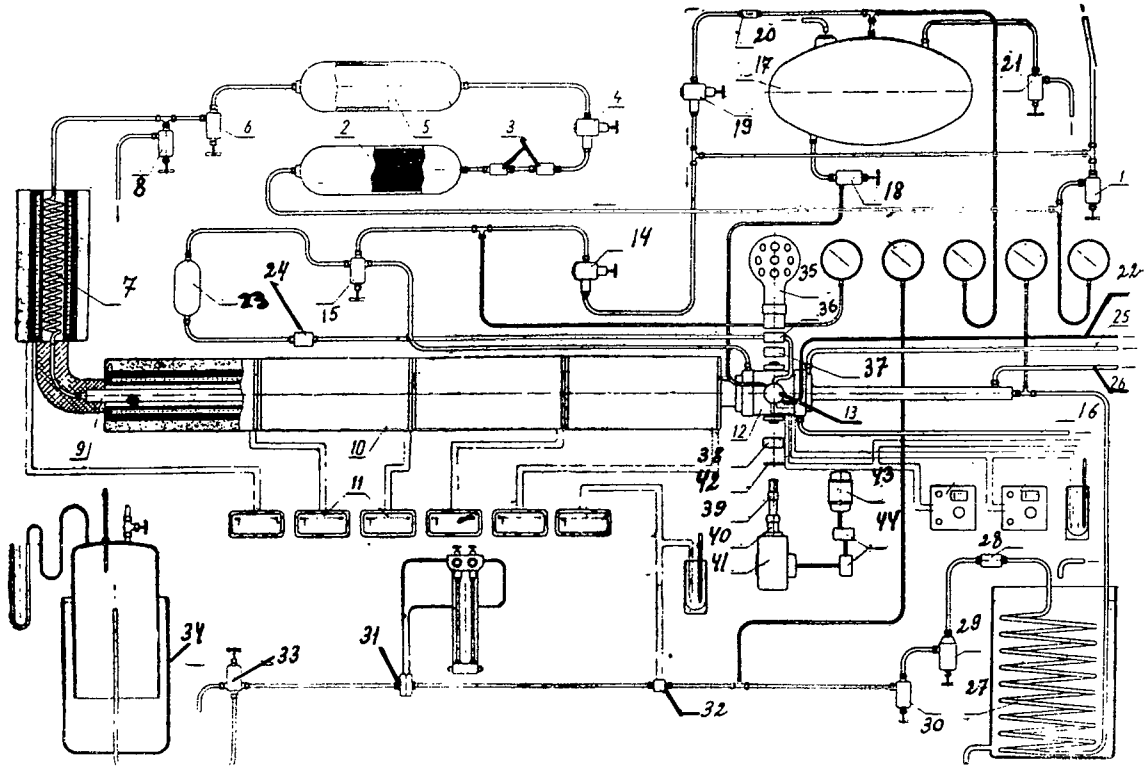

Figure 2. - Schematic of experimental apparatus.

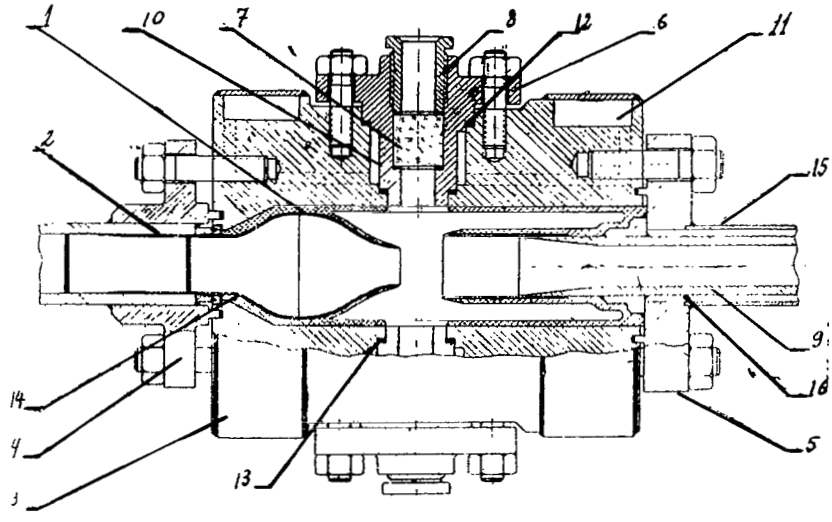

Figure 3. - Horizontal section of high pressure chamber.

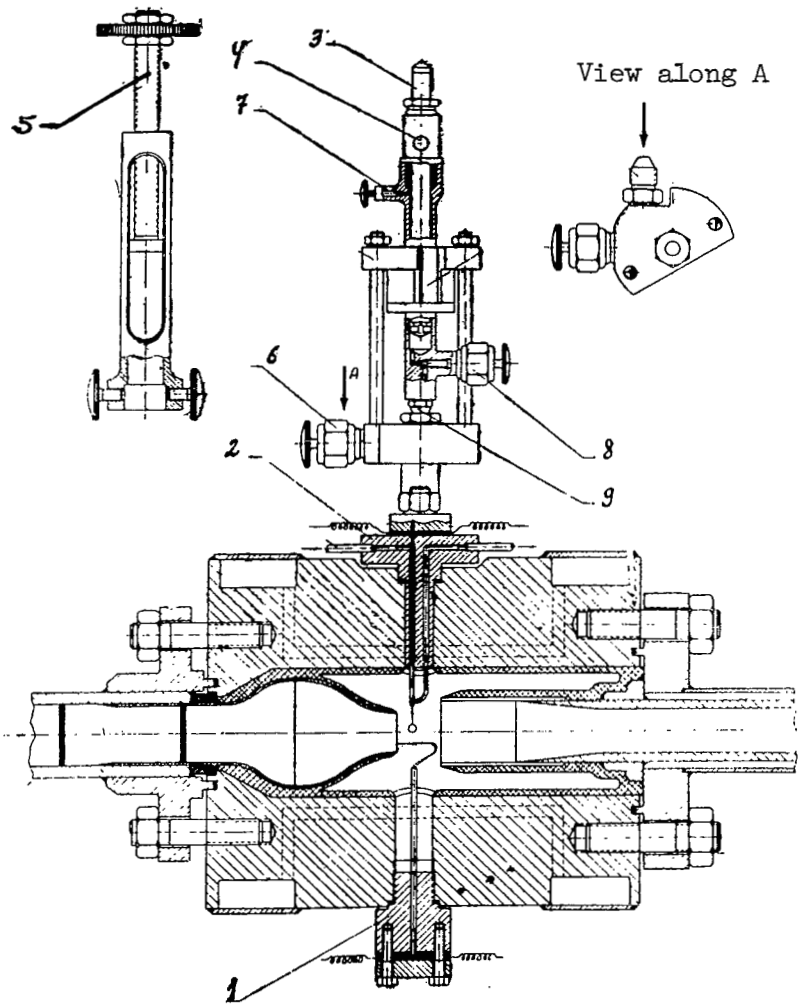

Figure 4. - Vertical section of high pressure chamber.

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